

# On the Origin of the Dichotomy of Early-Type Galaxies: The Role of Dry Mergers and AGN Feedback

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## ABSTRACT

Using a semi-analytical model for galaxy formation, combined with a large  $N$ -body simulation, we investigate the origin of the dichotomy among early-type galaxies. In qualitative agreement with previous studies and with numerical simulations, we find that boxy galaxies originate from mergers with a progenitor mass ratio  $n < 2$  and with a combined cold gas mass fraction  $F_{\text{cold}} < 0.1$ . Our model accurately reproduces the observed fraction of boxy systems as a function of luminosity and halo mass, for both central galaxies and satellites. After correcting for the stellar mass dependence, the properties of the last major merger of early-type galaxies are independent of their halo mass. This provides theoretical support for the conjecture of Pasquali et al. (2007) that the stellar mass (or luminosity) of an early-type galaxy is the main parameter that governs its isophotal shape. If wet and dry mergers mainly produce disk and boxy early-types, respectively, the observed dichotomy of early-type galaxies has a natural explanation within the hierarchical framework of structure formation. Contrary to naive expectations, the dichotomy is independent of AGN feedback. Rather, we argue that it owes to the fact that more massive systems (i) have more massive progenitors, (ii) assemble later, and (iii) have a larger fraction of early-type progenitors. Each of these three trends causes the cold gas mass fraction of the progenitors of more massive early-types to be lower, so that their last major merger involved less cold gas (was more “dry”). Finally, our model predicts that (i) less than 10 percent of all early-type galaxies form in major mergers that involve two early-type progenitors, (ii) more than 95 percent of all boxy early-type galaxies with  $M_* \lesssim 2 \times 10^{10} h^{-1} M_\odot$  are satellite galaxies, and (iii) about 70 percent of all low mass early-types do not form a supermassive black hole binary at their last major merger. The latter may help to explain why low mass early-types have central cusps, while their massive counterparts have cores.

**Key words:** dark matter — galaxies: elliptical and lenticular — galaxies: interactions — galaxies: structure — galaxies: formation

## 1 INTRODUCTION

Ever since the seminal paper by Davies et al. (1983) it is clear that early-type galaxies (ellipticals and lenticulars, hereafter ETGs) can be split in two distinct sub-classes. Davies et al. showed that bright ETGs typically have little rotation, such that their flattening must originate from anisotropic pressure. This is consistent with bright ellipticals being in general triaxial. Low luminosity ellipticals, on the other hand, typically have rotation velocities that are consistent with them being oblate isotropic rotators (see Emsellem et al. 2007 and Cappellari et al. 2007 for a more contemporary description). These different kinematic classes

also have different morphologies and different central surface brightness profiles. In particular, bright, pressure-supported systems usually have boxy isophotes and luminosity profiles that break from steep outer power-laws to shallow inner cusps (often called ‘cores’). The low luminosity, rotation supported systems, on the other hand, often reveal disk isophotes and luminosity profiles with a steep central cusp (e.g., Bender 1988; Nieto et al. 1988; Ferrarese et al. 1994; Gebhardt et al. 1996; Rest et al. 2001; Lauer et al. 2005, 2006). Finally, the bimodality of ETGs has also been found to extend to their radio and X-ray properties. Objects which are radio-loud and/or bright in soft X-ray emission generally have boxy isophotes, while disk ETGs are mostly radio-quiet and faint in soft X-rays (Bender et al. 1989; Pellegrini 1999, 2005; Ravindranath et al. 2001).

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Recently, Hao et al. (2006) constructed a homogeneous sample of 847 ETGs from the SDSS DR4 catalogue (Adelman-McCarthy et al. 2006), and analyzed their isophotal shapes. This sample was used by Pasquali et al. (2007; hereafter P07) to investigate the relative fractions of disk and boxy ETGs as function of luminosity, stellar mass and environment. They found that the disk fraction decreases smoothly with increasing (*B*-band) luminosity, stellar mass, and halo mass, where the latter is obtained from the SDSS group catalogue of Weinmann et al. (2006). In addition, the disk fraction is found to be higher for satellite galaxies than for central galaxies in a halo of the same mass. These data provide a powerful benchmark against which to test models for the formation of ETGs.

Within the framework of hierarchical structure formation, elliptical galaxies are generally assumed to form through major mergers (e.g., Toomre & Toomre 1972; Schweizer 1982; Barnes 1988; Hernquist 1992; Kauffmann, White & Guiderdoni 1993). In this case, it seems logical that the bimodality in their isophotal and kinematical properties must somehow be related to the details of their merger histories. Using dissipationless *N*-body simulations it has been shown that equal mass mergers of disk galaxies mainly result in slowly rotating ETGs with boxy (but sometimes disk) isophotes, while mergers in which the mass ratio between the progenitor disks is significantly different from unity mainly yields disk ETGs (Negroponte & White 1983; Barnes 1988; Hernquist 1992; Bendo & Barnes 2000; Naab & Burkert 2003; Bournaud et al. 2004, 2005; Naab & Trujillo 2006). However, simulations that also include a dissipative gas component and star formation have shown that the presence of even a relatively small amount of cold gas in the progenitors results in a merger remnant that resembles a disk elliptical even when the mass ratio of the progenitors is close to unity (Barnes & Hernquist 1996; Naab et al. 2006a; Cox et al. 2006a). This suggests that boxy ETGs can only form out of dry, major mergers (see also discussion in Faber et al. 1997). In this paper we test this paradigm using a semi-analytical model for galaxy formation and the observational constraints of P07.

Our study is similar to those of Khochfar & Burkert (2005; hereafter KB05) and Naab et al. (2006b; hereafter N06), who also used semi-analytical models to explore whether the dichotomy of elliptical galaxies can be related to their merger properties. However, our analysis differs from theirs on the following grounds.

- We use a numerical *N*-body simulation to construct the merger histories of dark matter haloes. The models of KB05 and N06, on the other hand, used merger trees based on the extended Press-Schechter (EPS) formalism (e.g., Lacey & Cole 1993). As we will show, this results in significant differences.
- Because of our use of numerical *N*-body simulations, our model more accurately traces the dynamical evolution of dark matter subhaloes with their associated satellite galaxies. In particular, it takes proper account of dynamical friction, tidal stripping and the merging between subhaloes.
- Contrary to KB05 and N06, we include a prescription for the feedback from active galactic nuclei (AGN) in our semi-analytical model.
- Our semi-analytical model is tuned to reproduce the

luminosity function and the color-bimodality of the redshift zero galaxy population (see Kang et al. 2005). The works of KB05 and N06 do not mention such a comparison.

- Our criteria for the production of boxy ETGs are different from those used in KB05 and N06.
- We use a much larger, more homogeneous data set to constrain the models.

This paper is organized as follows. In Section 2 we describe our *N*-body simulation and semi-analytical model, and outline the methodology. The results are described in Section 3 and discussed in Section 4. We summarize our findings in Section 5

## 2 METHODOLOGY

The aim of this paper is to investigate to what extent semi-analytical models of galaxy formation can reproduce the ecology of ETGs, in particular the fractions of disk and boxy systems as function of luminosity and halo mass. Partially motivated by numerical simulations of galaxy mergers, both with and without gas, we adopt a framework in which (i) ETGs are red and dominated by a spheroidal component, (ii) ETGs are the outcome of major mergers, (iii) the remnant is boxy if the merger is sufficiently “dry” (i.e., the progenitors have little or no cold gas) and sufficiently “major” (i.e., the progenitors have roughly equal masses) and (iv) a boxy elliptical becomes a disk elliptical if newly accreted material builds a sufficiently large stellar disk.

### 2.1 *N*-body simulation and model descriptions

In order to have accurate merger trees, and to be able to follow the dynamical evolution of satellite galaxies, we use a numerical simulation of the evolution of dark matter which we populate with galaxies using a state-of-the-art semi-analytical model for galaxy formation. The numerical simulation has been carried out by Jing & Suto (2002) using a vectorized-parallel  $P^3M$  code. It follows the evolution of  $512^3$  particles in a cosmological box of  $100h^{-1}$  Mpc, assuming a flat  $\Lambda$ CDM ‘concordance’ cosmology with  $\Omega_m = 0.3$ ,  $\sigma_8 = 0.9$ , and  $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1} = 0.7$ . Each particle has a mass of  $6.2 \times 10^8 h^{-1} M_\odot$ . Dark matter haloes are identified using the friends-of-friends (FOF) algorithm with a linking length equal to 0.2 times the mean particle separation. For each halo thus identified we compute the virial radius,  $r_{\text{vir}}$ , defined as the *spherical* radius centered on the most bound particle inside of which the average density is 340 times the average density of the Universe (cf. Bryan & Norman 1998). The virial mass is simply defined as the mass of all particles that have halocentric radii  $r \leq r_{\text{vir}}$ . Since our FOF haloes have a characteristic overdensity of  $\sim 180$  (e.g., White 2002), the virial mass is typically smaller than the FOF mass.

Dark matter subhaloes within each FOF (parent) halo are identified using the SUBFIND routine described in Springel et al. (2001). In the present study, we use all haloes and subhaloes with masses down to  $6.2 \times 10^9 h^{-1} M_\odot$  (10 particles). Using 60 simulation outputs between  $z = 15$  and  $z = 0$ , equally spaced in  $\log(1+z)$ , Kang et al. (2005; hereafter K05) constructed the merger history for each (sub)halo

in the simulation box, which are then used in the semi-analytical model. In what follows, whenever we refer to a *halo*, we mean a virialized object which is not a sub-structure of a larger virialized object, while *subhaloes* are virialized objects that orbit within a halo. In addition, (model) galaxies associated with haloes and subhaloes are referred to as central galaxies and satellites, respectively.

The semi-analytical model used to populate the haloes and subhaloes with galaxies is described in detail in K05, to which we refer the reader for details. Briefly, the model assumes that the baryonic material accreted by a dark matter halo is heated to the virial temperature. The gas then cools radiatively and settles down into a centrifugally supported disk, in which the star formation rate is proportional to the total amount of cold gas, and inversely proportional to the dynamical time of the disk. The energy feedback from supernova is related to the initial stellar mass function (IMF) and proportional to the star formation rate. It is assumed that the gas that is reheated by supernova feedback remains bound to the host halo so that it can cool back onto the disk at later stages. When the subhalo associated with a satellite galaxy is dissolved in the numerical simulation the satellite galaxy becomes an “orphan” galaxy, which is assumed to merge with the central galaxy of the parent halo after a dynamical friction time (computed assuming standard Chandrasekhar dynamical friction). When two galaxies merge, the outcome is assumed to depend on their mass ratio  $n \equiv M_1/M_2$  with  $M_1 \geq M_2$ . If  $n \leq 3$  the merger is assumed to result in the formation of an elliptical galaxy, and we speak of a “major merger”. Any cold gas available in both progenitors is turned into stars. This is supported by hydrodynamical simulations, which show that major mergers cause the cold gas to flow to the center where the resulting high gas density triggers a starburst (e.g., Barnes & Hernquist 1991, 1996; Mihos & Hernquist 1996; Springel 2000; Cox et al. 2006a,b; Di Matteo et al. 2007). A new disk of cold gas and stars may form around the elliptical if new gas can cool in the halo of the merger remnant, thus giving rise to a disk-bulge system. If  $n > 3$  we speak of a “minor merger” and we simply add the cold gas of the less massive progenitor to that of the disk of the more massive progenitor, while its stellar mass is added to the bulge of the massive progenitor. The semi-analytical model also includes a prescription for “radio-mode” AGN feedback as described in Kang, Jing & Silk (2006; see also Section 3.2). This ingredient is essential to prevent significant amounts of star formation in the brightest galaxies, and thus to ensure that these systems are predominantly members of the red sequence (e.g., Cattaneo et al. 2006; De Lucia et al. 2006; Bower et al. 2006; Croton et al. 2006). Finally, luminosities for all model galaxies are computed using the predicted star formation histories and the stellar population models of Bruzual & Charlot (2003). Throughout we assume a Salpeter IMF and we self-consistently model the metallicities of gas and stars, including metal-cooling.

As shown in K05 and Kang et al. (2006) this model accurately fits, among others, the galaxy luminosity function at  $z = 0$ , the color bimodality of the  $z = 0$  galaxy population, and the number density of massive, red galaxies out to  $z \sim 3$ . We emphasize that in this paper we use this model without changing any of its parameters.

## 2.2 Predicting Isophotal Shapes

In our model we determine whether an elliptical galaxy is disk or boxy as follows. Using the output at  $z = 0$  we first identify the early-type (E/S0) galaxies based on two criteria. First of all, following Simien & de Vaucouleurs (1986), we demand that an ETG has a bulge-to-disk ratio in the  $B$ -band of  $L_{B,\text{bulge}}/L_{B,\text{total}} \geq 0.4$ . In addition, we require the  $B - V$  color of the galaxy to be red. Following Hao et al. (2006) and P07, we adopt  $B - V > 0.8$ . We have verified that none of our results are sensitive to the exact choice of these selection criteria.

Having thus identified all ETGs at  $z = 0$ , we subsequently trace their formation histories back until their last major merger, and register the mass ratio  $n$  of the merger event, as well as the total cold gas mass fraction at that epoch, defined as

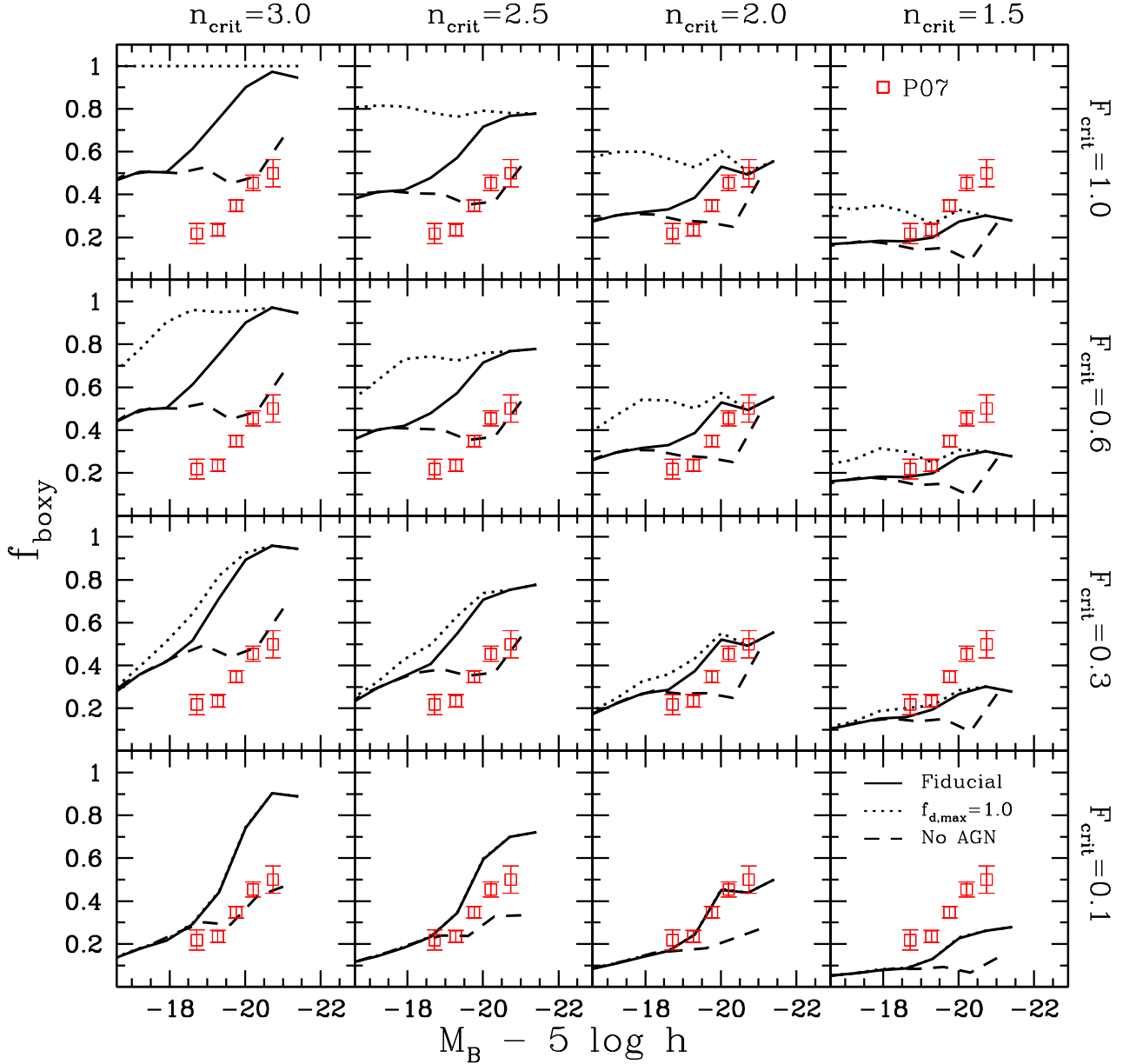
$$F_{\text{cold}} \equiv \frac{\sum_{i=1}^2 M_{\text{cold},i}}{\sum_{i=1}^2 (M_{\text{cold},i} + M_{*,i})} \quad (1)$$

Here  $M_{\text{cold},i}$  and  $M_{*,i}$  are the cold gas mass and stellar mass of progenitor  $i$ , respectively. We adopt the hypothesis that the merger results in a boxy elliptical if, and only if,  $n < n_{\text{crit}}$  and  $F_{\text{cold}} < F_{\text{crit}}$ . The main aim of this paper is to use the data of P07 to constrain the values of  $n_{\text{crit}}$  and  $F_{\text{crit}}$ , and to investigate whether a model can be found that is consistent with the observed fraction of boxy (disky) ETGs as function of both galaxy luminosity and halo mass.

The final ingredient for determining whether an ETG is disk or boxy is the potential regrowth of a stellar disk. Between its last major merger and the present day, new gas in the halo of the remnant may cool out to form a new disk. In addition, the ETG may also accrete new stars and cold gas via minor mergers (those with  $n > 3$ ). Any cold gas in those accreted systems is added to the new disk, where it is allowed to form new stars. Whenever the stellar disk has grown sufficiently massive, its presence will reveal itself in the isophotes, and the system changes from being boxy to being disk. To take this effect into account, we follow KB05 and we reclassify a boxy system as disk if at  $z = 0$  it has grown a disk with a stellar mass that contributes more than a fraction  $f_{d,\text{max}}$  of the total stellar mass in the galaxy. In our fiducial model we set  $f_{d,\text{max}} = 0.2$ . This is motivated by Rix & White (1990), who have shown that if an embedded stellar disk contains more than  $\sim 20$  percent of the total stellar mass, the isophotes of its host galaxy become disk. Note that the same value for  $f_{d,\text{max}}$  has also been used in the analysis of KB05.

## 3 RESULTS

In Figure 1 we show the fraction of boxy ETGs,  $f_{\text{boxy}}$ , as a function of the luminosity in the  $B$ -band (in the AB system). Open squares with errorbars (reflecting Poisson statistics) correspond to the data of P07, while the various lines indicate the results obtained from three different models that we describe in detail below. The (Poisson) errors on these model predictions are comparable to those on the P07 data and are not shown for clarity. Each column and row show,

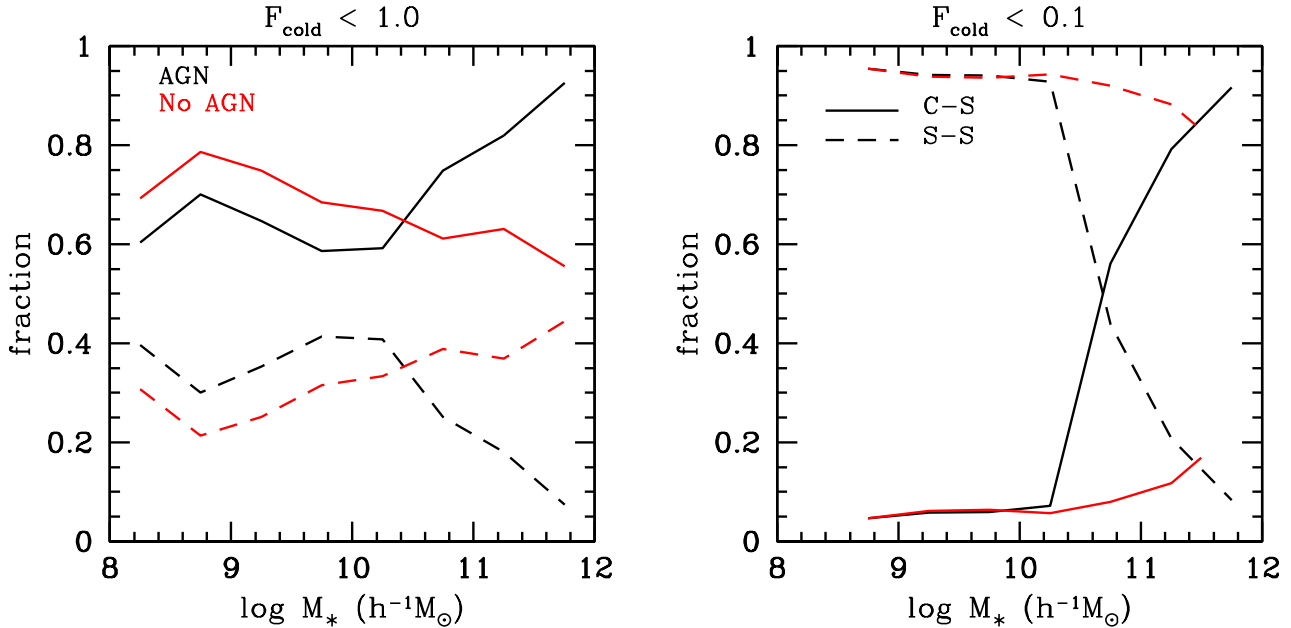


**Figure 1.** The boxy fraction of ETGs as function of their  $B$ -band magnitude (in the AB system). The open, red squares with (Poissonian) errorbars correspond to the data of P07, and are duplicated in each panel. The solid, dotted and dashed lines correspond to the three models discussed in the text. Different columns and rows correspond to different values for the critical progenitor mass ratio,  $n_{\text{crit}}$ , and the critical cold gas mass fraction,  $F_{\text{crit}}$ , respectively, as indicated.

respectively, the results for different values of  $n_{\text{crit}}$  and  $F_{\text{crit}}$  as indicated.

We start our investigation by setting  $f_{d,\text{max}} = 1$ , which implies that the isophotal shape of an elliptical galaxy (disky or boxy) is assumed to be independent of the amount of mass accreted since the last major merger. Although we don't consider this realistic, it is a useful starting point for our investigation, as it clearly separates the effects of  $n_{\text{crit}}$  and  $F_{\text{crit}}$  on the boxy fraction. The results thus obtained from our semi-analytical model with AGN feedback are shown in Figure 1 as dotted lines. If we assign the isophotal shapes of ETGs depending only on the progenitor mass ratio  $n$ , which corresponds to setting  $F_{\text{crit}} = 1$ , we obtain the boxy fractions shown in the upper panels. In agreement with KB05 (see

their Figure 1) this results in a boxy fraction that is virtually independent of luminosity, in clear disagreement with the data. Note that, for a given value of  $n_{\text{crit}}$ , our boxy fractions are significantly higher than in the model of KB05. For example, for  $n_{\text{crit}} = 2$  we obtain a boxy fraction of  $\sim 0.6$ , while KB05 find that  $f_{\text{boxy}} \sim 0.33$ . This mainly reflects the difference in the type of merger trees used. As discussed above, we use the merger trees extracted from a  $N$ -body simulation, while KB05 use monte-carlo merger trees based on the EPS formalism. It is well known that EPS merger trees predict masses for the most massive progenitors that are too large (e.g., Lacey & Cole 1994; Somerville et al. 2000; van den Bosch 2002; Benson, Kamionkowski & Hassani 2005). This implies that the number of mergers with a small progenitor



**Figure 2.** The fractions of last major mergers between centrals and satellites (C-S; solid lines) and between two satellites (S-S; dashed lines) that result in the formation of an ETG as function of its stellar mass at  $z = 0$ . Results are shown for all ETGs (left-hand panel) and for those with  $F_{\text{cold}} < 0.1$  (right-hand panel). Black and red lines correspond to models with and without AGN feedback, respectively. Low mass ETGs that form in dry mergers, and hence end up being boxy, mainly form out of S-S mergers. At the massive end, the fraction of ETGs that form out of S-S mergers with  $F_{\text{cold}} = 0.1$  depends strongly on the presence or absence of AGN feedback. See text for detailed discussion.

mass ratio  $n$  will be too small, which explains the difference between our results and those of KB05. Using cosmological SPH simulations, Maller et al. (2006) found that the distribution of merger mass ratios scales as  $dN/dn \propto n^{-0.8}$ . This means that 60 percent of all galaxy mergers with  $n < 3$  have a progenitor mass ratio  $n < 2$ , in excellent agreement with our results.

The dotted lines in the remaining panels of Figure 1 show the results obtained for three different values of the maximum cold gas mass fraction,  $F_{\text{crit}} = 0.6, 0.3$ , and  $0.1$ . Lowering  $F_{\text{crit}}$  has a strong impact on the boxy fraction of low-luminosity ETGs, while leaving that of bright ETGs largely unaffected. As we show in §4 this mainly owes to the fact that  $F_{\text{cold}}$  decreases strongly with increasing luminosity. Consequently, by changing  $F_{\text{crit}}$  we can tune the slope of the relation between  $f_{\text{boxy}}$  and luminosity, while  $n_{\text{crit}}$  mainly governs the absolute normalization. We obtain a good match to the P07 data for  $n_{\text{crit}} = 2$  and  $F_{\text{crit}} = 0.1$  (third panel in lowest row). This implies that boxy ETGs only form out of relatively dry and violent mergers, in good agreement with numerical simulations.

### 3.1 The influence of disk regrowth

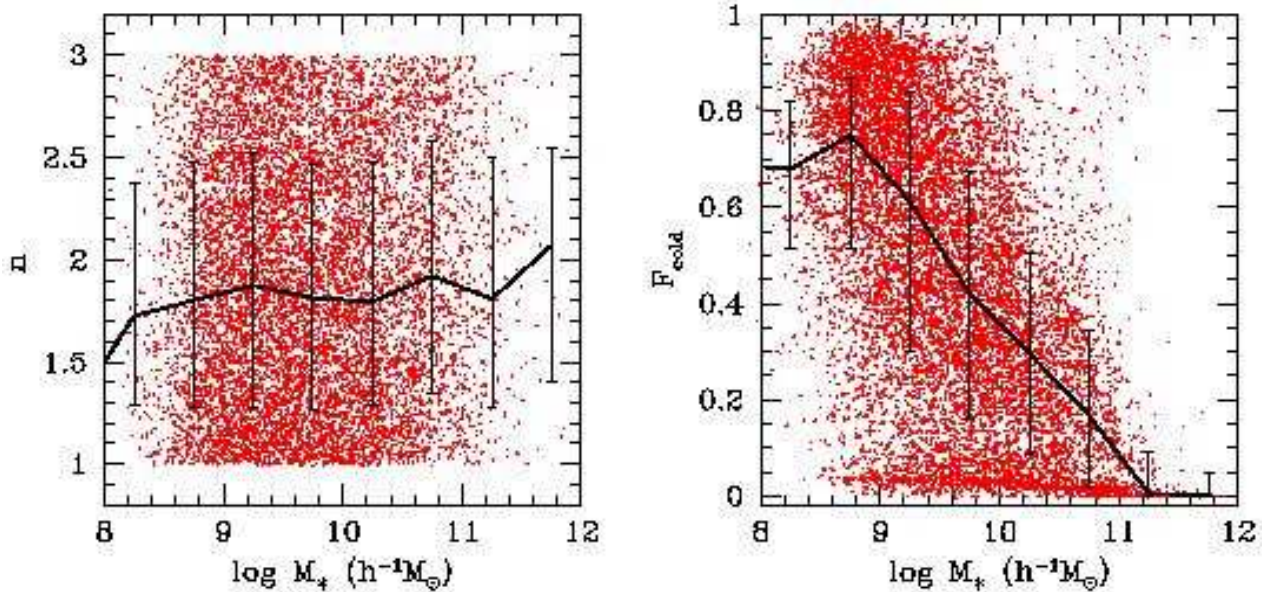
The analysis above, however, does not consider the impact of the growth of a new disk around the merger remnant. Since this may turn boxy systems into disk systems, it can have a significant impact on the predicted  $f_{\text{boxy}}$ . We now take this effect into account by setting  $f_{d,\text{max}}$  to its fiducial value of 0.2.

The solid lines in Fig. 1 show the boxy fractions thus obtained. A comparison with the dotted lines shows that the

newly formed disks only cause a significant decrease of  $f_{\text{boxy}}$  at the faint end. At the bright end, AGN feedback prevents the cooling of hot gas, therewith significantly reducing the rate at which a new disk can regrow<sup>†</sup>. However, when  $F_{\text{crit}} = 0.1$ , we obtain the same boxy fractions for  $f_{d,\text{max}} = 0.2$  as for  $f_{d,\text{max}} = 1$ , even at the faint end. This implies that we obtain the same conclusions as above: matching the data of P07 requires  $n_{\text{crit}} \simeq 2$  and  $F_{\text{crit}} \simeq 0.1$ . In other words, our constraints on  $n_{\text{crit}}$  and  $F_{\text{crit}}$  are robust to exactly how much disk regrowth is allowed before it reveals itself in the isophotes.

Why do faint ETGs with  $F_{\text{cold}} < 0.1$  not regrow significant disks, while does with  $F_{\text{cold}} > 0.1$  do? Note that during the last major merger, the entire cold gas mass is converted into stars in a starburst. Therefore, it is somewhat puzzling that the galaxy’s ability to regrow a disk depends on its cold gas mass fraction at the last major merger. As it turns out, this owes to the fact that progenitors with a low cold gas mass fraction are more likely to be satellite galaxies. Fig. 2 plots the fractions of ETGs with last major mergers between a central galaxy and a satellite (C-S; solid lines) and between two satellites (S-S; dashed lines). Note that in our model, S-S mergers occur whenever their dark matter subhaloes in the  $N$ -body simulation merge. Results are shown for all ETGs (left-hand panel), and for only those ETGs that have  $F_{\text{cold}} < 0.1$  (right-hand panel). In our fiducial model with AGN feedback (black lines) the most massive ETGs almost exclusively form out of C-S mergers. Since a satellite galaxy can never become a central galaxy, this is

<sup>†</sup> In the absence of cooling, the only way in which a galaxy can (re)grow a disk is via minor mergers.



**Figure 3.** The progenitor mass ratio,  $n$ , (left-hand panel) and the cold gas mass fraction at the last major merger,  $F_{\text{cold}}$ , (right-hand panel) as function of the  $z = 0$  stellar mass,  $M_*$ , of ETGs. Solid lines with errorbars indicate the median and the 20<sup>th</sup> and 80<sup>th</sup> percentiles of the distributions. While the mass ratio of the progenitors of early-type galaxies is independent of its stellar mass,  $F_{\text{cold}}$  decreases strongly with increasing  $M_*$ .

consistent with the fact that virtually all massive ETGs at  $z = 0$  are central galaxies (in massive haloes). Roughly 40 percent of all low mass ETGs have a last major merger between two satellite galaxies. However, when we only focus on low mass ETGs with  $F_{\text{cold}} < 0.1$ , we find that  $\sim 95$  percent of their last major mergers are between two satellite galaxies. Since the  $z = 0$  descendants of S-S mergers will also be satellites, this implies that virtually all boxy ETGs with  $M_* \lesssim 2 \times 10^{10} h^{-1} M_\odot$  are satellite galaxies. Furthermore, since satellite galaxies do not have a hot gas reservoir (at least not in our semi-analytical model) they can not regrow a new disk by cooling. This explains why for  $F_{\text{crit}} = 0.1$  the boxy fractions are independent of the value of  $f_{d,\text{max}}$ .

### 3.2 The role of AGN feedback

Our semi-analytical model includes “radio-mode” AGN feedback, similar to that in Croton et al. (2006), in order to suppresses the cooling in massive haloes. This in turn shuts down star formation in the central galaxies in these haloes, so that they become red. In the absence of AGN feedback, new gas continues to cool making the central galaxies in massive haloes overly massive and too blue (e.g., Benson et al. 2003; Bower et al. 2006; Croton et al. 2006; Kang et al. 2006). In order to study its impact on  $f_{\text{boxy}}$  as function of luminosity, we simply turn off AGN feedback in our model. Although this results in a semi-analytical model that no longer fits the galaxy luminosity function at the bright end, and results in a color-magnitude relation with far too many bright, blue galaxies, a comparison with the models discussed above nicely isolates the effects that are directly due to our prescription for AGN feedback.

The dashed lines in Figure 1 show the predictions of our model without AGN feedback (and with  $f_{d,\text{max}} = 0.2$ ).

A comparison with our fiducial model (solid lines) shows that apparently the AGN feedback has no impact on  $f_{\text{boxy}}$  for faint ETGs with  $M_B - 5 \log h \gtrsim -18$ . At the bright end, though, the model without AGN feedback predicts boxy fractions that are significantly lower (for reasons that will be discussed in §4.2). Consequently, the luminosity dependence of  $f_{\text{boxy}}$  is much weaker than in the fiducial case. The only model that comes close to matching the data of P07 is the one with  $n_{\text{crit}} = 3$  and  $F_{\text{crit}} = 0.1$ . We emphasize, though, that this model is not realistic. In addition to the fact that this semi-analytical model does not fit the observed luminosity function and color magnitude relation, a value of  $n_{\text{crit}} = 3$  is also very unlikely: numerical simulations have clearly shown that mergers with a mass ratio near 1:3 almost invariably result in diskly remnants (e.g., Naab & Burkert 2003).

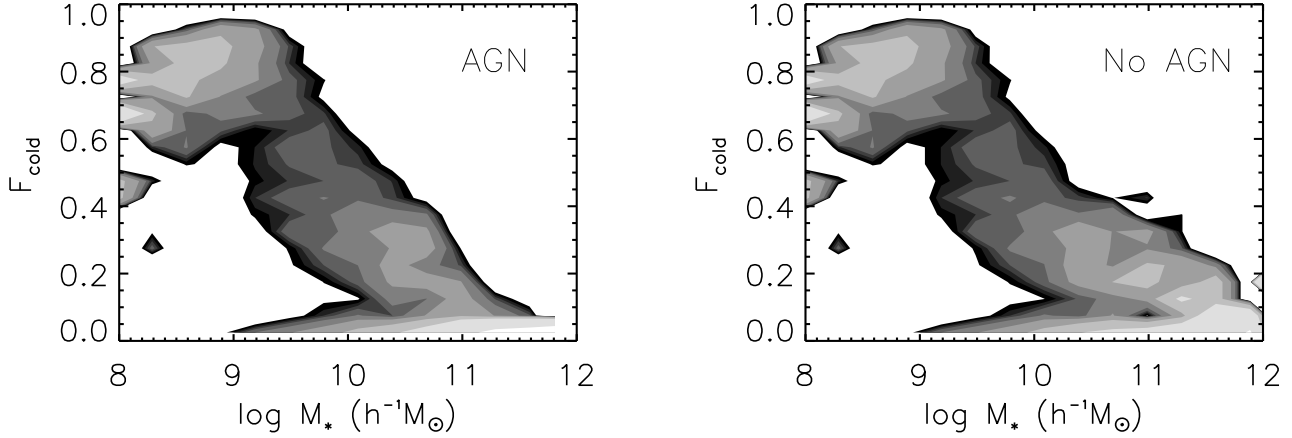
## 4 DISCUSSION

### 4.1 The Origin of the ETG Dichotomy

We now examine the physical causes for the various scalings noted above. We start by investigating why our fiducial model with  $n_{\text{crit}} = 2$  and  $F_{\text{crit}} = 0.1$  is successful in reproducing the luminosity dependence of  $f_{\text{boxy}}$ , i.e., why it predicts that the boxy fraction increases with luminosity. Given the method used to assign isophotal shapes to the ETGs in our model, there are three possibilities: (i) brighter ETGs have smaller progenitor mass ratios, (ii) brighter ETGs have progenitors with smaller cold gas mass fractions, or (iii) brighter ETGs have less disk regrowth after their last major merger.

We can exclude (i) from the fact that the models that ignore disk regrowth (i.e., with  $f_{d,\text{max}} = 1$ ) and that ignore





**Figure 4.** Contour plots for the number density of ETGs as function of their present day stellar mass,  $M_*$ , and their cold gas mass fraction at the last major merger,  $F_{\text{cold}}$ . Results are shown both for our fiducial model with AGN feedback (left-hand panel), as well as for the model without AGN feedback (right-hand panel). In both cases a clear bimodality is apparent: ETGs with large and low masses formed out of dry and wet mergers, respectively. Note that this bimodality is present independent of the presence of AGN feedback.

the cold gas mass fractions (i.e., with  $F_{\text{crit}} = 1$ ) predict that the boxy fraction is roughly independent of luminosity (dotted lines in upper panels of Fig. 1). This suggests that the distribution of  $n$  is roughly independent of the (present day) luminosity of the ETGs. This is demonstrated in the left-hand panel of Fig. 3, where we plot  $n$  as function of,  $M_*$ , the stellar mass at  $z = 0$ . Each dot corresponds to an ETG in our fiducial model, while the solid black line with the errorbars indicates the median and the 20<sup>th</sup> and 80<sup>th</sup> percentiles of the distribution: clearly the progenitor mass ratio is independent of  $M_*$ .

The boxy fraction of our best-fit model with  $n_{\text{crit}} = 2$  and  $F_{\text{crit}} = 0.1$  is also independent of the regrowth of disks, which is evident from the fact that the models with  $f_{d,\text{max}} = 1$  (dotted lines) and  $f_{d,\text{max}} = 0.2$  (solid lines) predict boxy fractions that are indistinguishable. Therefore option (iii) can also be excluded, and the luminosity dependence of  $f_{\text{boxy}}$  thus has to indicate that the progenitors of more luminous ETGs have a lower gas mass fraction. That this is indeed the case can be seen from the right-hand panel of Fig. 3 which shows  $F_{\text{cold}}$  as function of  $M_*$ . Once again, the solid black line with the errorbars indicates the median and the 20<sup>th</sup> and 80<sup>th</sup> percentiles of the distribution. Note that  $F_{\text{cold}}$  decreases strongly with increasing stellar mass; the most massive ETGs form almost exclusively from dry mergers with  $F_{\text{cold}} < 0.1$ .

The left-hand panel of Fig. 4 shows a different rendition of the relation between  $F_{\text{cold}}$  and  $M_*$ . Contours indicate the number density,  $\phi(F_{\text{cold}}, M_*)$ , of ETGs in the  $F_{\text{cold}}-M_*$  plane, normalized by the total number of ETGs at each given  $M_*$ -bin, i.e.,

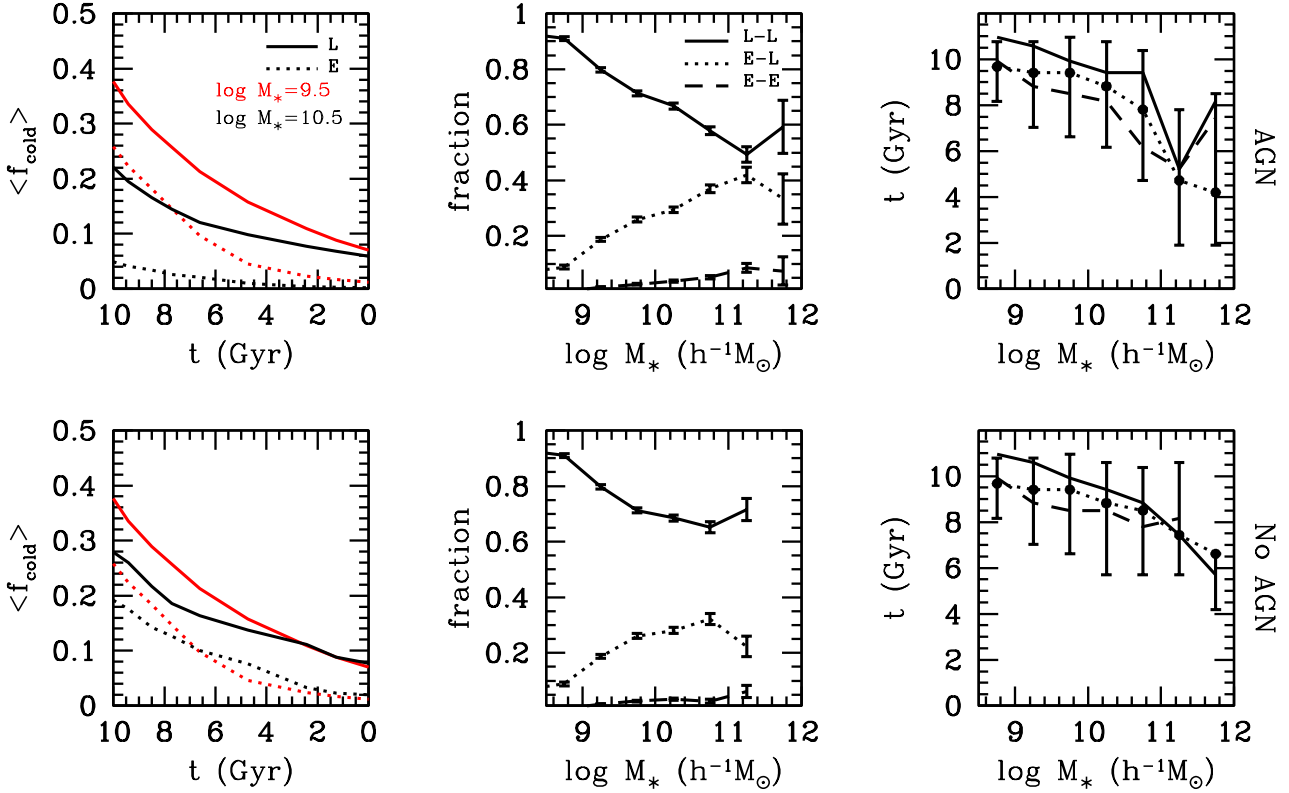
$$\int_0^1 \phi(F_{\text{cold}}, M_*) dF_{\text{cold}} = 1 \quad (2)$$

Note that  $\phi(F_{\text{cold}}, M_*)$  is clearly bimodal: low mass ETGs with  $M_* \lesssim 3 \times 10^9 h^{-1} M_\odot$  have high  $F_{\text{cold}}$ , while the progenitors of massive ETGs have low cold gas mass fractions. Clearly, if wet and dry mergers produce disk and boxy ellipticals, respectively, this bimodality is directly responsible for the ETG dichotomy.

What is the physical origin of this bimodality? It is

tempting to expect that it owes to AGN feedback. After all, in our model AGN feedback is more efficient in more massive galaxies. Since more massive ETGs have more massive progenitors, one could imagine that their cold gas mass fractions are lower because of the AGN feedback. However, the right-hand panel of Fig. 4 shows that this is not the case. Here we show  $\phi(F_{\text{cold}}, M_*)$  for the model without AGN feedback. Somewhat surprisingly, this model predicts almost exactly the same bimodality as the model with AGN feedback. Their are subtle differences, which have a non-negligible effect on the boxy fractions and which will be discussed in §4.2 below. However, it should be clear from Fig. 4 that the overall bimodality in  $\phi(F_{\text{cold}}, M_*)$  is not due to AGN feedback.

In order to explore alternative explanations for the bimodality, Fig. 5 shows some relevant statistics. Upper and lower panels correspond to the models with and without AGN feedback, respectively. Here we focus on our fiducial model with AGN feedback; the results for the model without AGN feedback will be discussed in §4.2. The upper left-hand panel shows the average cold gas mass fraction of individual galaxies,  $\langle f_{\text{cold}} \rangle$ , as function of lookback time. Note that here we use  $f_{\text{cold}}$  to distinguish it from  $F_{\text{cold}}$ , which indicates the cold gas mass fraction of the combined progenitors taking part in a major merger, as defined in eq. (1). Results are shown for galaxies of two different (instantaneous) stellar masses,  $M_* = 3 \times 10^9 h^{-1} M_\odot$  (red lines) and  $M_* = 3 \times 10^{10} h^{-1} M_\odot$  (black lines), and for two (instantaneous) types: early-types (dotted lines) and late-types (solid lines). Following N06, here we define early-types as systems with a bulge-to-total stellar mass ratio of 0.6 or larger; contrary to our  $z = 0$  selection criteria described in §2.1, we do not include a color selection, simply because the overall color of the galaxy population evolves as function of time. First of all, note that  $\langle f_{\text{cold}} \rangle$  of galaxies of given type and given mass decreases with increasing time (i.e., with decreasing lookback time). This is simply due to the consumption by star formation. Secondly, at a given time, early-type galaxies have lower gas mass fractions than late-type galaxies. This mainly owes to the fact that at a major merger, which creates an early-type, all the available cold gas is consumed in a starburst. Consequently, each early-type starts its life



**Figure 5.** Various statistics of our semi-analytical models. Upper and lower panels refer to our models with and without AGN feedback, respectively. *Left-hand panels:* The average cold gas mass fraction of individual galaxies as function of lookback time  $t$ . Results are shown for galaxies of two different (instantaneous) stellar masses,  $M_* = 3 \times 10^9 h^{-1} M_\odot$  (red lines) and  $M_* = 3 \times 10^{10} h^{-1} M_\odot$  (black lines), and for two (instantaneous) types: early-types (dotted lines) and late-types (solid lines). *Middle panels:* The fractions of late-late (L-L; solid lines), early-late (E-L; dotted lines) and early-early (E-E; dashes lines) type mergers as function of the  $z = 0$  stellar mass of the resulting ETG. *Right-hand panels:* The average lookback time to the last major merger of  $z = 0$  ETGs as function of their  $z = 0$  stellar mass. Results are shown separately for L-L mergers (solid line), E-L mergers (dotted line), and E-E mergers (dashed line). The errorbars indicate the 20<sup>th</sup> and 80<sup>th</sup> percentiles of the distribution of the E-L mergers. For clarity, we do not show these percentiles for the L-L and E-E mergers, though they are very similar. See text for detailed discussion.

with  $f_{\text{cold}} = 0$ . Finally, massive galaxies have lower gas mass fractions than their less massive counterparts. This owes to the fact that more massive galaxies live, on average, in more massive haloes, which tend to form (not assemble!) earlier thus allowing star formation to commence at an earlier epoch (see Neistein et al. 2006). In addition, the star formation efficiency used in the semi-analytical model is proportional to the mass of the cold gas times  $M_{\text{vir}}^{0.73}$ . As discussed in K05, this scaling with the halo virial mass is required in order to match the observed  $\langle f_{\text{cold}} \rangle(M_*)$  at  $z = 0$  (see also Cole et al. 1994, 2000; De Lucia et al. 2004).

The middle panel in the upper row of Fig. 5 shows what kind of galaxy types are involved in the last major mergers of present-day ETGs. Solid, dotted and dashed curves show the fractions of L-L, E-L and E-E mergers, where ‘L’ and ‘E’ refer to late-types and early-types, respectively. As above, these types are based solely on the bulge-to-total mass ratio of the galaxy and not on its color. In our semi-analytical model, the lowest mass ETGs almost exclusively form via L-L mergers. With increasing  $M_*$ , however, there is a pronounced decrease of the fraction of L-L mergers, which are mainly replaced by E-L mergers. The fraction of E-E mergers increases very weakly with increasing stellar mass but never exceeds 10 percent. Thus, although boxy ellipticals

form out of dry mergers, these are not necessarily mergers between early-type galaxies. In fact, our model predicts that the vast majority of all dry mergers involve at least one late-type galaxy (though with a low cold gas mass fraction). This is in good agreement with the SPH simulation of Maller et al. (2006), who also find that E-E mergers are fairly rare. However, it is in stark contrast to the predictions of the semi-analytical model of N06, how find that more than 50 percent of the last major mergers of massive ellipticals are E-E mergers. We suspect that the main reason for this strong discrepancy is the fact that N06 used merger trees based on the EPS formalism.

Finally, the upper right-hand panel of Fig. 5 plots the average lookback time to the last major merger of ETGs as function of their present day stellar mass. Results are shown separately for L-L mergers (solid line), E-L mergers (dotted line), and E-E mergers (dashed line). Clearly, more massive ETGs assemble later (at lower lookback times). This mainly owes to the fact that more massive galaxies live in more massive haloes, which themselves assemble later (cf. Lacey & Cole 1993; Wechsler et al. 2002; van den Bosch 2002; Neistein et al. 2006; De Lucia et al. 2006). In addition, it is clear that at fixed stellar mass, E-E mergers occur later than



L-L mergers, with E-L mergers in between. This difference, however, is small compared to the scatter.

If we combine all this information, we infer that the bimodality in  $\phi(F_{\text{cold}}, M_*)$  owes to the following three facts:

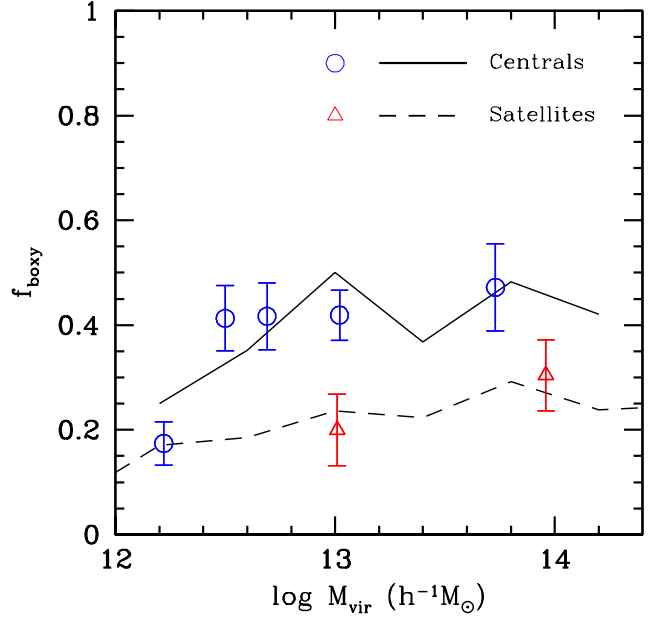
- More massive ETGs have more massive progenitors (this follows from the fact that  $n$  is independent of  $M_*$ ). Since at a given time more massive galaxies of a given type have lower cold gas mass fractions,  $\langle F_{\text{cold}} \rangle$  decreases with increasing  $M_*$ .
- More massive ETGs assemble later (at lower redshifts). Galaxies of given mass and given type have lower  $\langle f_{\text{cold}} \rangle$  at later times. Consequently,  $\langle F_{\text{cold}} \rangle$  decreases with increasing  $M_*$ .
- More massive ETGs have a larger fraction of early-type progenitors. ETGs of a given mass have a lower cold gas mass fraction than late type galaxies of the same mass, at any redshift. In addition, E-L mergers occur at later times than L-L mergers. Both these effects also contribute to the fact that  $\langle F_{\text{cold}} \rangle$  decreases with increasing  $M_*$ .

#### 4.2 Is AGN feedback relevant?

A comparison of the upper and lower panels in Fig. 5 shows that the three effects mentioned above, and thus the bimodality in  $\phi(F_{\text{cold}}, M_*)$ , are present independent of whether or not the model includes feedback from active galactic nuclei. There are only two small differences: without AGN feedback massive ETGs (i) are more likely to result from L-L mergers, and (ii) have a higher  $\langle f_{\text{cold}} \rangle$  (cf. black dotted curves in the left-hand panels of Fig. 5). Both effects reflect that AGN feedback prevents the cooling of hot gas around massive galaxies, therewith removing an important channel for building a new disk. As is evident from Fig. 4, these two effects only have a very mild impact on  $\phi(F_{\text{cold}}, M_*)$ . We therefore conclude that *the bimodality of ETGs is not due to AGN feedback*.

This does not imply, however, that AGN feedback does not have an impact on the boxy fractions. As is evident from Fig. 1, the models with and without AGN feedback clearly predict different  $f_{\text{boxy}}$  at the bright end. To understand the origin of these differences, first focus on Fig. 4. Although both panels look very similar, upon closer examination one can notice that at  $M_* \gtrsim 10^{11} h^{-1} M_\odot$  the number density of ETGs with  $0.1 \lesssim F_{\text{cold}} \lesssim 0.25$  is significantly larger in the model without AGN feedback. In the model with AGN feedback these systems all have  $F_{\text{cold}} < 0.1$ . This explains why the model without AGN feedback predicts a lower boxy fraction for bright galaxies when  $F_{\text{crit}} = 0.1$ . However, this does not explain why  $f_{\text{boxy}}$  is also different when  $F_{\text{crit}} \geq 0.3$ . After all, for those models it should not matter whether  $F_{\text{cold}} = 0.05$  or  $F_{\text{cold}} = 0.25$ , for example. It turns out that in these cases the differences between the models with and without AGN feedback are due to the regrowth of a new disk; since AGN feedback suppresses the cooling of hot gas around massive galaxies, it strongly suppresses the regrowth of a new disk, thus resulting in higher boxy fractions.

Note however, that in ETGs with  $F_{\text{cold}} < 0.1$ , disk regrowth is always negligible. In the presence of AGN feedback this is due to the suppression of cooling in massive haloes. In the absence of AGN feedback it owes to the fact that only a very small fraction of ETGs are central galaxies. As can



**Figure 6.** The boxy fraction of ETGs as function of halo (group) mass. Red triangles (for satellite galaxies) and blue circles (for central galaxies) are taken from P07, and have been obtained using the galaxy group catalogue of Weinmann et al. (2006). Dashed and solid lines correspond to the predictions from our fiducial model.

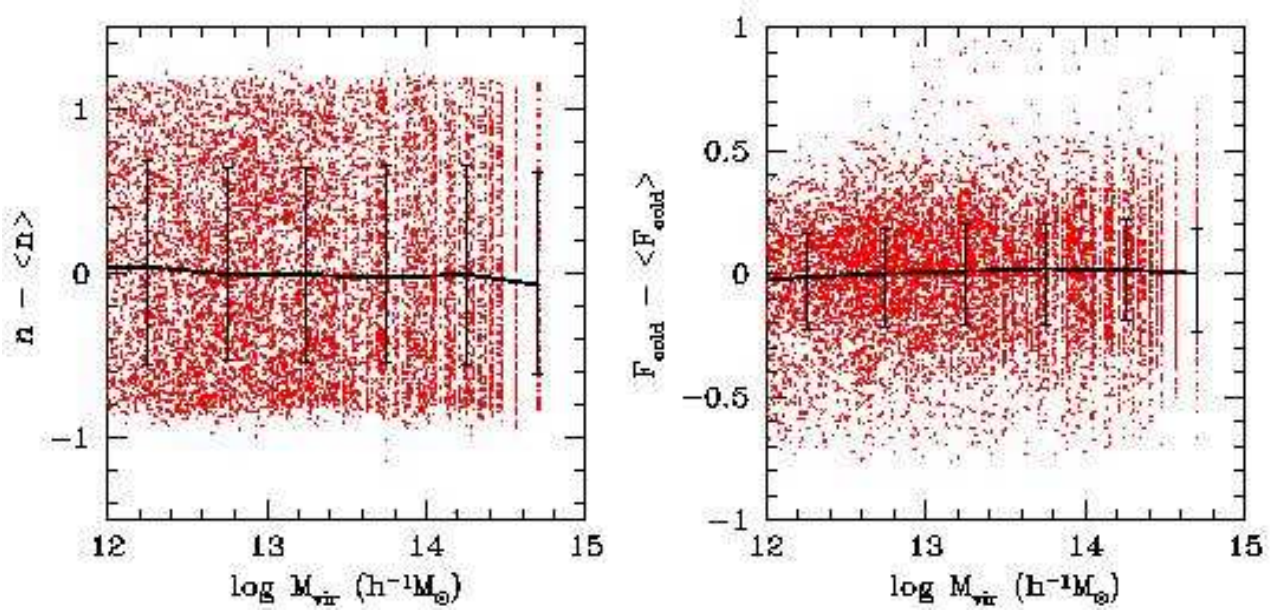
be seen from the right-hand panel of Fig. 2, more than 90 percent of the ETGs have last major mergers between two satellite galaxies (with AGN feedback this fraction is smaller than 20 percent). Since satellite galaxies do not have hot gas reservoirs, no significant disks can regrow around these systems.

#### 4.3 Environment dependence

Using the SDSS galaxy group catalogue of Weinmann et al. (2006), which has been constructed using the halo-based group finder developed by Yang et al. (2005), P07 investigated how  $f_{\text{boxy}}$  scales with group mass. They also split their sample in ‘central’ galaxies (defined as the brightest group members) and ‘satellites’. The open circles and triangles in Fig. 6 show their results for centrals and satellites, respectively. Although there are only two data points for the satellites, it is clear that central galaxies are more likely to be boxy than a satellite galaxy in a group (halo) of the same mass.

We now investigate whether our fiducial semi-analytic model that fits the luminosity dependence of the boxy fraction (i.e., the one with  $n_{\text{crit}} = 2$  and  $F_{\text{crit}} = 0.1$ ) can also reproduce these trends. The model predictions for the centrals and satellites are shown in Fig. 6 as solid and dashed lines, respectively. Here we have associated the halo virial mass with the group mass, and an ETG is said to be a central galaxy if it is the brightest galaxy in its halo. The model accurately reproduces the boxy fraction of both central and satellite galaxies. In particular, it reproduces the fact that  $f_{\text{boxy}}$  of central galaxies is higher than that of satellites in groups (haloes) of the same mass.

As shown in P07, the boxy fraction as function of group



**Figure 7.** The residuals of the relations between  $n$  and  $M_*$  (left panel) and  $F_{\text{cold}}$  and  $M_*$  (right panel) as functions of the virial mass of the halo in which the ETGs reside at  $z = 0$ . As in Fig. 3 the solid lines with errorbars indicate the mean and the 20<sup>th</sup> and 80<sup>th</sup> percentiles of the distributions. These show that after one corrects for the stellar mass dependence, the properties of the last major mergers of ETGs are independent of their halo mass.

mass, for both centrals and satellites, is perfectly consistent with the null-hypothesis that the isophotal shape of an ETG depends only on its luminosity; the fact that centrals have a higher boxy fraction than satellites in the same group, simply owes to the fact that the centrals are brighter. Also, the increase of  $f_{\text{boxy}}$  with increasing group mass simply reflects that more massive haloes host brighter galaxies. It therefore may not come as a surprise that our semi-analytical model that fits the luminosity dependence of  $f_{\text{boxy}}$  also fits the group mass dependencies shown in Fig. 6. It does mean, though, that in our model the merger histories of ETGs of a given luminosity do not strongly depend on the halo mass in which the galaxy resides.

To test this we proceed as follows. For each ETG in our model we compute  $\langle n \rangle$  and  $\langle F_{\text{cold}} \rangle$ , where the average is over all ETGs with stellar masses similar to that of the galaxy in question. Fig. 7 plots the residuals  $n - \langle n \rangle$  and  $F_{\text{cold}} - \langle F_{\text{cold}} \rangle$  as function of the virial mass,  $M_{\text{vir}}$ , of the halo in which they reside. This clearly shows that after one corrects for the stellar mass dependence, the properties of the last major merger of ETGs are indeed independent of their halo mass<sup>‡</sup>. This provides theoretical support for the conclusion of P07 that the stellar mass (or luminosity) of an ETG is the main parameter that determines whether it will be disk or boxy.

#### 4.4 The Origin of Cusps and Cores

As discussed in §1, the dichotomy of ETGs is not only restricted to their isophotal shapes. One other important aspect of the dichotomy regards the central density distribu-

tion of ETGs; while disk systems typically have cuspy profiles, the bright and boxy ellipticals generally reveal density profiles with a pronounced core. Here we briefly discuss how the formation of cusps and cores fits in the picture sketched above.

In the paradigm adopted here, low luminosity ETGs form mainly via wet mergers. Due to the fluctuating potential of the merging galaxies and the onset of bar instabilities, the gas experiences strong torques which causes a significant fraction of the gas to sink towards the center of the potential well where it undergoes a starburst (e.g., Shlosman, Frank & Begelman 1989; Barnes & Hernquist 1991; Mihos & Hernquist 1996). Detailed hydrodynamical simulations of gas-rich mergers (e.g., Springel & Hernquist 2005; Cox et al. 2006b) result in the formation of remnants with surface brightness profiles that are reminiscent of cuspy ETGs (John Kormendy, private communication). Hence, cusps seem a natural by-product of the dissipative processes associated with a wet merger.

Boxy ETGs, however, are thought to form via dry mergers. As can be seen from Fig. 5 roughly 35 percent of all massive ETGs originate from a last major merger that involves an early-type progenitor. If this progenitor contains a cusp, this will survive the merger, as most clearly demonstrated by Dehnen (2005). The only mergers that are believed to result directly in a remnant with a core, are mergers between pure stellar disks with a negligible  $f_{\text{cold}}$  (e.g., Cox et al. 2006a). Fig. 8 shows the cumulative distributions of the bulge-to-total stellar mass ratios of the progenitors of present day ETGs. Results are shown for ETGs in three mass ranges, as indicated. The probability that a progenitor of a massive ETGs (with  $M_* > 10^{11} h^{-1} M_{\odot}$ ) has a negligible bulge component ( $M_{*,\text{bulge}} < 0.01 M_*$ ) is only about 3 percent. Hence, we expect that only about 1 out of every 1000 major mergers that result in a massive ETG will have a remnant with

<sup>‡</sup> The fact that the distribution of the progenitor mass ratio  $n$  is independent of halo mass was also found by KB05

a core. And this is most likely an overestimate, since we did not take the cold gas mass fractions into consideration. Since the cusp accounts for only about one percent of the total stellar mass (e.g., Faber et al. 1997; Milosavljević et al. 2002), cold gas mass fractions of a few percent are probably enough to create a cusp via dissipational processes.

Therefore, an additional mechanism is required in order to create a core (i.e., destroy a cusp). Arguably the most promising mechanism is the orbital decay of a supermassive black hole (SMBH) binary, which can scour a core by exchanging angular momentum with the cusp stars (e.g., Begelman et al. 1980; Ebisuzaki et al. 1991; Quinlan 1996; Faber et al. 1997; Milosavljević et al. 2002; Merritt 2006a). Since virtually all spheroids contain a SMBH at their center, with a mass that is tightly correlated with the mass of the spheroid (e.g., Kormendy & Richstone 1995; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Marconi & Hunt 2003; Häring & Rix 2004), it is generally expected that such binaries are common in merger remnants (but see below).

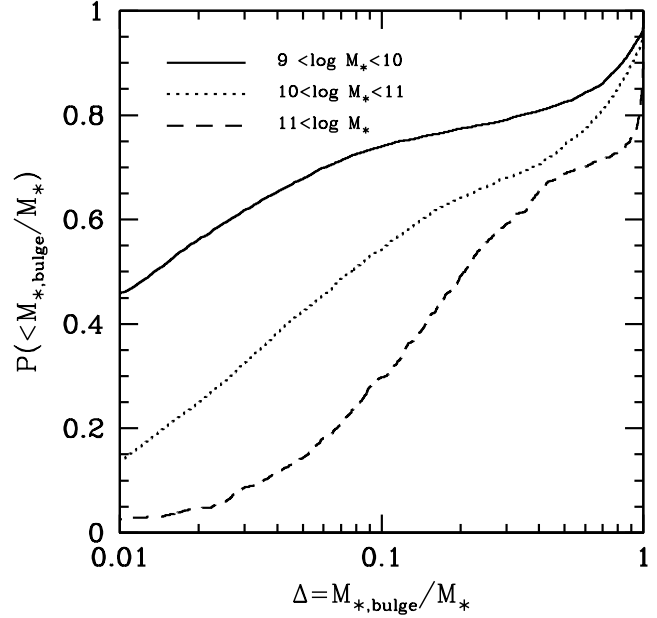
While offering an attractive explanation for the presence of cores in massive, boxy ETGs, this picture simultaneously poses a potential problem for the presence of cusps in disk ETGs. After all, if the progenitors of disk ETGs also harbor SMBHs, the same process could create a core in these systems as well. There are two possible ways out of this paradox: (i) low mass ETGs do not form a SMBH binary, or (ii) a cusp is regenerated after the two SMBHs have coalesced. We now discuss these two options in turn.

In order for a SMBH binary to form, dynamical friction must first deliver the two SMBHs from the two progenitors to the center of the newly formed merger remnant. This process will only be efficient if the spheroidal hosts of the SMBHs are sufficiently massive. Consider a (small) bulge that was part of a late-type progenitor which is now orbiting the remnant of its merger with another galaxy. Assume for simplicity that both the bulge and the merger remnant are purely stellar singular isothermal spheres ( $\rho \propto r^{-2}$ ) with velocity dispersions equal to  $\sigma_b$  and  $\sigma_g$ , respectively. Then, assuming that the bulge is on a circular orbit, with an initial radius  $r_i$ , Chandrasekhar's (1943) formula gives an infall time for the bulge of

$$t_{\text{infall}} \approx 3.3 \frac{r_i}{\sigma_g} \left( \frac{\sigma_g}{\sigma_b} \right)^3 \approx 4.7 \times 10^8 \text{ yr} \left( \frac{M_g}{M_b} \right) \quad (3)$$

(Merritt 2006b). Here we have used that  $r_i/\sigma_g \approx \sqrt{2} t_{\text{cross}}$  with  $t_{\text{cross}} \sim 10^8$  yr the galaxy crossing time. If the galaxy is the remnant of an equal mass merger, so that  $M_b \sim (\Delta/2)M_g$ , with  $\Delta$  the bulge-to-total stellar mass ratio of the late-type progenitor, we find that  $t_{\text{infall}}$  is equal to the Hubble time ( $1.3 \times 10^{10}$  yr) for  $\Delta \simeq 0.07$ . As can be seen from Fig. 8, about 70 percent of the low mass ETGs (with  $10^9 h^{-1} M_\odot < M_* < 10^{10} h^{-1} M_\odot$ ) have at least one progenitor with a stellar bulge-to-total mass ratio  $\Delta < 0.07$ . Therefore, we expect that a similar fraction will form without a SMBH binary, and thus will not form a core. For comparison, for massive ETGs (with  $M_* > 10^{11} h^{-1} M_\odot$ ) only about 20 percent of the progenitors will have a sufficiently small bulge to prevent the formation of a SMBH binary.

An alternative explanation for the presence of cusps in low mass ETGs is that the cusp is regenerated by star formation from gas present at the last major merger. However, as emphasized by Faber et al. (1997), this results in a serious



**Figure 8.** The cumulative probability that a progenitor of a  $z = 0$  ETG has a stellar bulge-to-total mass ratio less than  $M_{*,\text{bulge}}/M_*$ . Results are shown for the progenitors of ETGs in three stellar mass ranges, as indicated (masses are in  $h^{-1} M_\odot$ ). Note that the progenitors of more massive ETGs have significantly higher  $M_{*,\text{bulge}}/M_*$ . As discussed in the text, this may help to explain why low mass ETGs have cusps, while massive ones have cores.

timing problem, as it requires that the new stars must form after the SMBH binary has coalesced. Another potential problem with this picture, is that the cusp would be younger than the main body of the ETG which may lead to observable effects (i.e., cusp could be bluer than main body). However, in light of the results presented here, we believe that neither of these two issues causes a serious problem. First of all, the cold gas mass fractions involved with the last major merger, and hence the mass fraction that is turned into stars in the resulting starburst, is extremely large:  $\langle F_{\text{cold}} \rangle \sim 0.8$  (see Fig. 4). As mentioned above, a significant fraction of this gas is transported to the center, where it will function as an important energy sink for the SMBH binary, greatly speeding up its coalescence (Escala et al. 2004, 2005) and therewith reducing the timing problem mentioned above. In fact, the gas may well be the dominant energy sink, so that the pre-existing cusps of the progenitors are only mildly affected. But even if the cusps were destroyed, there clearly should be enough gas left to build a new cusp. In fact, if, as envisioned in our semi-analytical model, all the cold gas present at the last major merger is consumed in a starburst, a very significant fraction of the stars in the main body would also be formed in this starburst (not only the cusp). This would help to diminish potential population differences between the cusp and the main body of the ETG. In addition, as can be seen from the right-hand panels of Fig. 5, the last major merger of low luminosity ETGs occurred on average  $\sim 9.5$  Gyr ago. Hence, the stars made in this burst are not easily distinguished observationally from the ones that were already present before the last major merger.

To summarize, our semi-analytical model predicts that

the progenitors of ETGs have cold gas mass fractions and bulge-to-total mass ratios that offer a relatively natural explanation for the observed dichotomy between cusps and cores.

## 5 CONCLUSIONS

Using a semi-analytical model for galaxy formation, combined with a large  $N$ -body simulation, we have investigated the origin of the dichotomy among ETGs. In order to assign isophotal shapes to the ETGs in our model we use three criteria: an ETG is said to be boxy if (i) the progenitor mass ratio at the last major merger is  $n < n_{\text{crit}}$ , (ii) the total cold gas mass fraction of the sum of the two progenitors at the last major merger is  $F_{\text{cold}} < F_{\text{crit}}$ , and (iii) after its last major merger the ETG is not allowed to regrow a new disk with a stellar mass that exceeds 20 percent of the total stellar mass.

In agreement with KB05, we find that we can not reproduce the observed luminosity (or, equivalently, stellar mass) dependence of  $f_{\text{boxy}}$  if we assign isophotal shapes based only on the progenitor mass ratio. This owes to the fact that the distribution of  $n$  is virtually independent of the stellar mass,  $M_*$ , of the ETG at  $z = 0$ . Rather, to obtain a boxy fraction that increases with increasing luminosity one also needs to consider the cold gas mass fraction at the last major merger. In fact, we can accurately match the data of P07 with  $n_{\text{crit}} = 2$  and  $F_{\text{crit}} = 0.1$ . This implies that boxy galaxies originate from relatively violent and dry mergers with roughly equal mass progenitors and with less than 10 percent cold gas, in good agreement with numerical simulations (e.g., Naab et al. 2006a; Cox et al. 2006a). Our model also nicely reproduces the observed boxy fraction as function of halo mass, for both central galaxies and satellites. We have demonstrated that this owes to the fact that after one corrects for the stellar mass dependence, the properties of the last major merger of ETGs are independent of their halo mass. This provides theoretical support for the conjecture of P07 that the stellar mass (or luminosity) of an ETG is the main parameter that determines whether it will be disk or boxy.

Our model predicts a number density distribution,  $\phi(F_{\text{cold}}, M_*)$ , of ETGs in the  $F_{\text{cold}}-M_*$  plane that is clearly bimodal: low mass ETGs with  $M_* \lesssim 3 \times 10^9 h^{-1} M_{\odot}$  have high  $F_{\text{cold}}$ , while the progenitors of massive ETGs have low cold gas mass fractions. Clearly, if wet and dry mergers produce disk and boxy ellipticals, respectively, this bimodality is directly responsible for the ETG dichotomy. Contrary to naive expectations, we find that this bimodality is independent of the inclusion of AGN feedback in the model. Although AGN feedback is essential for regulating the luminosities and colors of the brightest galaxies (which end up as ETGs with AGN feedback, but as blue disk-dominated systems without AGN feedback), it does not explain the bimodality among ETGs. Rather, this bimodality is due to the fact that more massive ETGs (i) have more massive progenitors, (ii) assemble later, and (iii) have a larger fraction of early-type progenitors. Each of these three trends causes the cold gas mass fraction of the progenitors of more massive ETGs to be lower, and thus its last major merger to be dryer. In conclusion, the dichotomy among ETGs has a

very natural explanation within the hierarchical framework of structure formation and does not require AGN feedback.

We also examined the morphological properties of the progenitors of present day ETGs (at the epoch of the last major merger). Indicating early- and late-type galaxies with ‘E’ and ‘L’, respectively, we find that the lowest mass ETGs almost exclusively form via L-L mergers. With increasing  $M_*$ , however, there is a pronounced decrease of the fraction of L-L mergers, which are mainly replaced by E-L mergers. The E-E mergers, however, never contribute more than 10 percent, in good agreement with the SPH simulations of Maller et al. (2006). Thus, although boxy ellipticals form out of dry mergers, these only rarely involve two early-type systems.

Since satellite galaxies do not have a hot corona from which new gas cools down, they typically have lower cold gas mass fractions than central galaxies of the same mass. Consequently, dry mergers are preferentially mergers between two satellite galaxies. In fact, since a satellite galaxy can not become a central galaxy, our model predicts that more than 95 percent of all boxy ETGs with  $M_* \lesssim 2 \times 10^{10} h^{-1} M_{\odot}$  are satellites.

We also find that the progenitors of less massive ETGs typically have lower bulge-to-total mass ratios. In fact, for ETGs with present day stellar masses in the range  $10^9 h^{-1} M_{\odot} < M_* < 10^{10} h^{-1} M_{\odot}$  we find that almost half of the progenitors at the last major merger have bulges that do not contribute more than one percent to the total stellar mass. This may have important implications for the observed dichotomy between cusps and cores in ETGs. Cores are believed to form via the scouring effect of a SMBH binary, that arises when the SMBHs associated with the spheroidal components of the progenitor galaxies form a bound pair. This requires both spheroids to sink to the center of the potential well of the merger remnant via dynamical friction. However, if the time scale for this infall exceeds the Hubble time, no SMBH binary will form, thus preventing the creation of a core. Using our prediction for the bulge-to-total mass ratios of progenitor galaxies, and a simple estimate based on Chandrasekhar’s dynamical friction formula, we have estimated that  $\sim 70$  percent of low mass ETGs in the aforementioned mass range will not form a SMBH binary. For massive ETGs with  $M_* > 10^{11} h^{-1} M_{\odot}$  this fraction is only  $\sim 20$  percent. This may help to explain why low mass ETGs have steep cusps, while massive ETGs have cores.

Finally, in those low mass systems that do form a SMBH binary, the large cold gas mass fraction at its last major merger ( $\langle F_{\text{cold}} \rangle \simeq 0.8$ ) provides more than enough raw material for the regeneration of a new cusp. In addition, a large fraction of the cold gas will sink to the center due to angular momentum transfer where it will function as an important energy sink for the SMBH binary. As shown by Escala et al. (2004, 2005), this can cause a tremendous acceleration of the coalescence of the SMBHs, largely removing the timing problem interjected by Faber et al. (1997).

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